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Monte Carlo Simulation of Energy Distribution of Radiation Field

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Abstract

Monte Carlo method is used to simulate transport process of γ photon in a medium modeled as a cube of water. By introducing a simulation method to calculate the energy distribution of γ-ray source radiation field, we simulate the energy distribution of the radiation field for ^{125}I spot source and array source in both homogeneous and inhomogeneous media. The radiation features of the radiation field are also studied. Our results provide valuable references for clinical medicine.

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Keywords: Monte Carlo method; radiation field; simulation

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1. Introduction

Radiotherapy is mainly applied to the treatment of malignant tumors. Nowadays, more than 70 percent of tumor patients receive radiation therapy to various degrees with the continuing advancement of the treatment techniques. However, during the treatment, normal tissues around the tumors inevitably receive certain degrees of radiation dose, which brings enormous harms to the patients' health. How to calculate precisely the radiation dose, eliminate tumor cells to the utmost, and meanwhile prevent normal cells from unnecessary harms, has become a hot subject in medical physics worldwide.

From the perspective of radiotherapy, the most suitable short-range radiation source must satisfy the following criteria: 1) the rays must have sufficient penetrating ability within human bodies and can be shielded easily at the same time, and 2) the half-life of the radionuclide cannot be too long and it can be made into miniature source [1] conveniently. At present, frequently-used radiation sources in treatment mainly consist of ^{125}I, ^{192}Ir, and ^{103}Pd, commonly referred to as "seed" sources [2] for their small volume. As seed sources enter human body, the absorption and scattering of the rays by the tissues around the sources lead to the decay of the ray strength to various degrees, directly influencing the energy distribution of the radiation field around the sources. Therefore, it is crucial to the increase of healing effect that one chooses correctly the kind of rays and photon energy, calculates rigorously the dose distribution of radiation field, and selects proper radiation sources in view of the tumor shapes [3].

Currently, it is widely accepted that Monte Carlo method of dose calculation has replaced conventional methods, resulting in sizable improvement of precision. E. Mainegra [4] et al. has used Monte Carlo software to simulate the dose distribution of radiation field of the ^{169}Yb source within human blood vessels and their results agree well with the experimental data. In this paper, we calculate the dose distribution of radiation field for spot source and array source choosing ^{125}I as the source model and our results provide valuable references for the clinical application of radiotherapy.

2. Monte Carlo Simulation Method

2.1. Monte Carlo Simulation and energy deposition method

Monte Carlo method is a kind of statistical-experiment approach, which is unique and of extremely high simulation quality. On the basis of a physical model and using statistical sampling techniques, it simulates directly particles' whole transport process: the particles' generation, entry into the medium, absorption by the medium, or escape from the medium. When Monte Carlo method is used to simulate the energy distribution of radiation field of γ-ray source ^{125}I in medium (human body), the calculation mainly involves the γ photons' transport process and interactions with the medium. Within the energy range from a few keV to several MeV, the interactions of γ photons with the medium mainly include the photoelectric effect, Compton effect, and the electron-pair effect. Other interactions are negligible due to their small probabilities. Because the interactions of γ photons with the medium can create secondary photons and electrons in both Compton scattering and electron-pair effect, the transport process of γ photons in human body can be regarded as a photon-electron coupled transport process, which has a very complicated reaction mechanism and is hard to be solved by usual numerical methods. When calculating γ photons' energy deposition with Monte Carlo method, one needs to track the transport processes of the γ photons as well as those of the secondary photons (We neglect the simulation of the secondary electrons in experiment assuming that all of them deposit energy in the medium after their interactions with the medium.). The history of a photon emitted from the source comes to an end until the γ source photon and all the secondary photons are simulated to the end of their histories. The total energy deposition (the energy lost by the photon in the medium) of each γ photon in the medium is equal to the sum of the energy deposition of the γ source photon and all of the secondary photons after the interactions with the medium [5, 6]. In experiment, one records the number and energy deposition of the γ photons in specified region by using the energy deposition method, and then calculates the three-dimensional energy distribution of the radiation field using the EGS4 computation software.

2.2. Framework of Monte Carlo program design

Simulating γ-photon transport by Monte Carlo method [7] mainly includes three processes: 1) random sampling of γ source photon distribution, 2) sampling of photons in space, energy, and movement direction, and 3) recording photon number and energy deposition. The state of motion of a γ photon in medium can be described by a set of state parameters $S=\left(\vec{r},E,\vec{\Omega}\right)$, which consists of three state parameters, namely the photon's spatial position $\vec{r}$, energy E and movement direction $\vec{\Omega}$. The purpose of sampling of γ source photon distribution is to generate the photon's initial state $S_0=\left(\vec{r}_0,E,\vec{\Omega}_0\right)$; if the

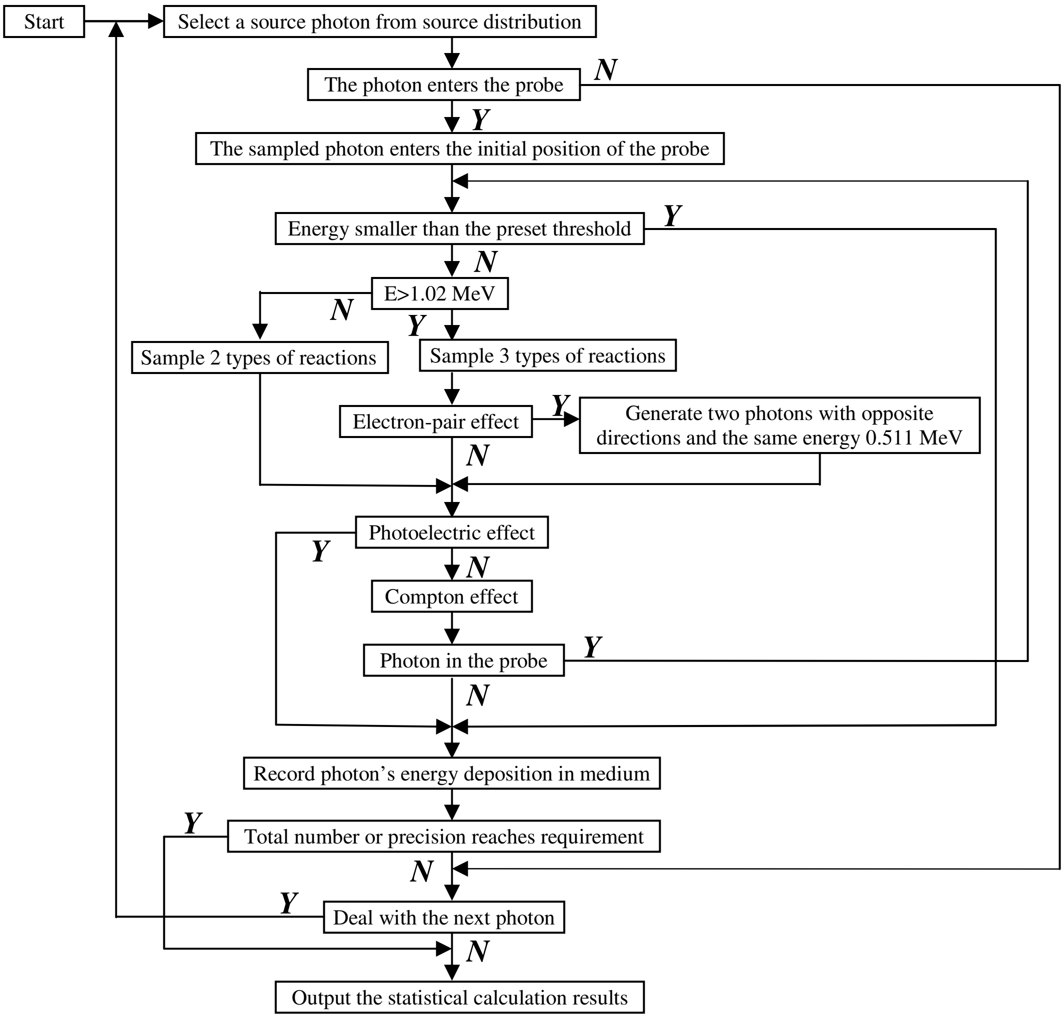

Fig. 1. Flow chart of the simulation software for photons in medium.

state of the photon after m collisions is $S_m = (\vec{r}_m, E, \vec{\Omega}_m)$, states S_m(m=0,1,2,…) can be determined by sampling with given S_{m-1}. In experiments, the spatial position $\vec{r}_m$ of the γ photon can be determined by sampling of the photon mean free path. The energy E_m and movement direction $\vec{\Omega}_m$ of the γ photon can be determined by sampling of the interaction types between the photon and medium. When the γ photon's energy satisfies $E > 1.02MeV$, sampling of three types of reactions (photoelectric effect, Compton scattering, and electron-pair effect) will be carried out. When the γ photon's energy satisfies $E < 1.02MeV$, only two types of reactions (photoelectric effect and Compton scattering) will be sampled. If the γ photon is absorbed after interaction with the medium or the photon energy is smaller than the given threshold energy, the photon's random swimming stops and its energy deposits (disappears) in the medium. In this case, one needs to record the photon number and energy deposition, and meanwhile simulate the random swimming of the next photon until the number of the simulated photons reaches the experiment requirement. The procedure of experiment simulation is shown in figure 1 [8, 9].

EGS (Electron-Gamma Shower) program, one of the utility softwares based on Monte Carlo computation method, is a large-scale general purpose software package for simulating electron-photon shower process, which is offered free of charge by SLAC National Accelerator Laboratory. It can simulate electron-photon shower process in an arbitrary geometry for particles with energies from a few keV up to several TeV [10]. One of the advantages of EGS software package is that it is slightly limited by geometrical conditions and does not increase computation time with the increase of the geometric dimension [5]. EGS is a powerful tool for computing energy distribution of radiation source in complicated biological tissues (for example, human body) and it is of great value to applications in the field of medical physics.

3. Monte Carlo Simulation for Energy Distribution of ^{125}I Radiation Field

3.1. Simulation model

In simulation, radiation source is set to be ^{125}I and photons with radiation energy 0.0355 MeV are chosen to be simulated. Table 1 lists the basic physics parameters [11] of the source.

Table 1. Physical parameters of radionuclide ^{125}I

Half-life (d)	59.4

Radiation	Medium model	Positions and arrangement of radiation source	Position of the region

Main photon energy (MeV)	0.0274; 0.0314; 0.0355
Air kerma rate constant [cGy.cm^2/(MBq.h)]	0.0352

Water and human-body soft tissues have comparable density and so do aluminum and human-body bone tissues. The energy decay and absorption coefficients of γ photons are also similar in these two pairs of media, respectively [1]. Therefore, water and aluminum can substitute for human-body soft tissues and bone tissues in simulation, respectively. We designed two kinds of medium models for the simulation. Model I is homogeneous water (H_2O), whose geometry is a cube of side length 10 cm. Model II comprises two kinds of media: water and aluminum, which are used to simulate biological soft tissues and bone tissues, respectively. Its geometry is a water cube of side length 10 cm, which contains an aluminum cube of side length 1 cm inside. If the center of the water cube is placed at the coordinate (0, 0, 0), the center coordinate of the aluminum cube is (2.5, 1.5, 0).

In medium models, spot source as well as positions and arrangement of the spot source array are regarded as the main variables. Information of energy distribution in radiation field can be gained by recording photon energy deposition in given region of the radiation field. Table 2 lists ^{125}I spot source as well as the positions and arrangement of the spot source array.

Using the Monte Carlo software called EGS4, We simulated 1 million photons and recorded the photon energy deposition in given regions of the radiation field. Then we carried out data acquisition of the EGS4 calculation results, processed the data by using the smooth interpolation method, and output three-dimensional figures using MATLAB.

source model			for recording data
Model 1	Water, cube of side length 10 cm	Spot source, situated at the center of the medium cube	A plane through the sources and parallel to the faces of the cube
Model 2	Water, cube of side length 10 cm	5 spot sources, aligned with a space of 1 cm on a line through the center of the medium cube, the line parallel to the faces of the cube, central spot source at the center of the cube	A plane through the sources and parallel to the faces of the cube
Model 3	Water, cube of side length 10 cm	4 spot sources, placed on the plane through the center and parallel to the faces of the cube, coordinates of the spots: (12.5, 12.5, 13), (17.5, 12.5, 8), (12.5, 17.5,13), (17.5,17.5,8)	A plane through the sources and parallel to the faces of the cube
Model 4	Water, cube of side length 10 cm	5 spot sources, placed on the plane through the center and parallel to the faces of the cube, aligned on a cross with one at the center of the cube and others 3 cm away from the center of the cube	A plane through the sources and parallel to the faces of the cube
Model 5	Water, cube of side length 10 cm	5 spot sources, placed on a plane through the center and parallel to the faces of the cube, aligned with equal space on a circle of radius 3 cm	A plane through the sources and parallel to the faces of the cube
Model 6	Water cube of side length 10 cm with an aluminum cube of side length 1 cm embedded inside	5 spot sources, placed on a plane through the center and parallel to the faces of the cube, aligned with equal spaces on a circle of radius 3 cm	A plane through the sources and parallel to the faces of the cube

Table 2. Positions and arrangement of ^{125}I spot source and spot-source array

3.2. Calculation results and analysis

Figure 2-7 simulate the energy distribution of the radiation field on the plane through the sources [12, 13] and parallel to the faces of the cube for different arrangements of the spot sources and spot-source arrays, respectively. In these figures, the vertical coordinates denote the relative dose distribution and the horizontal coordinates the distance of the radiation sources from the coordinate origin. The simulation results show that the energy distribution of the radiation field varies with the position and arrangement of the radiation sources, and the homogeneity of the medium has certain influences on the energy distribution.

Figure 2 is the energy distribution on the plane through the source and parallel to the faces of the water cube for the spot source. The feature of the distribution is that the radiation field of the spot source is isotropic in the homogeneous medium and the strength of the radiation field decreases sharply with increase of the distance between the field spot and source spot, which is consistent with the inverse square law of the field strength.

Figure 3-6 indicates the energy distribution of the radiation field for different arrangements of spot-source arrays in homogeneous water cubes, respectively. The simulation results show that the energy distribution of the radiation field varies with the arrangement of the spot-source array.

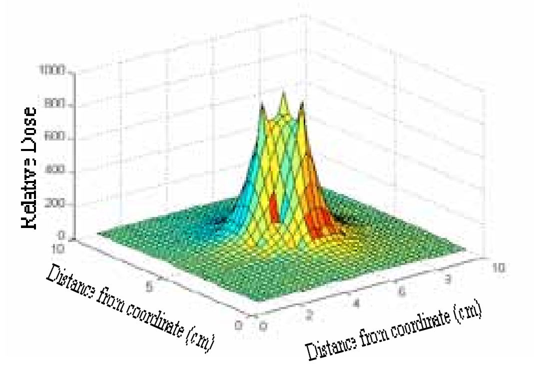

Fig. 2. Radiation field energy distribution of model 1, spot source placed at the center of the homogeneous water cube

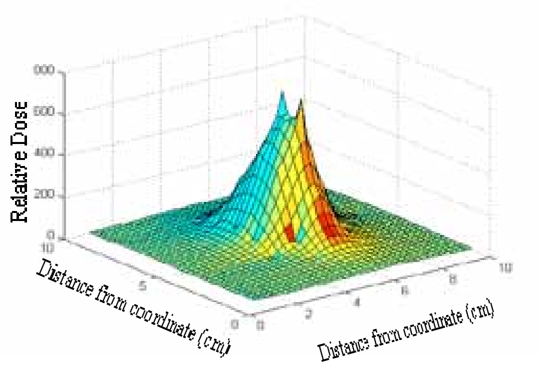

Fig. 3. Radiation field energy distribution of model 2, 5 spot sources aligned on a line with a space of 1 cm and the middle spot source placed at the center of the homogeneous water cube.

Figure 3 shows the energy distribution on the plane through the spot-source line and parallel to the faces of the water cube for 5 spot sources aligned on a line. Figure 3 indicates that its radiation field distribution is similar to that of Fig. 2 in the feature that its distribution is also isotropic. However, its peak is slightly different from that of Fig. 2. Figure 4 shows the results for 4 spot sources aligned on the same plane. This figure indicates that the radiation field distribution is anisotropic: the absorption dose is stronger on one side of the medium showing two stronger absorption peaks and the absorption is homogeneous on the other side of the medium. Figure 5 gives the results for the cross-like sources and shows the feature that the radiation field distribution tends to be homogeneous and isotropic on the plane through the sources and parallel to the faces of the cube. The figures of the radiation field distribution demonstrate that the radiation field of the 5-spot-source arrays is the superposition of the spot sources, which obeys exactly the superposition principle.

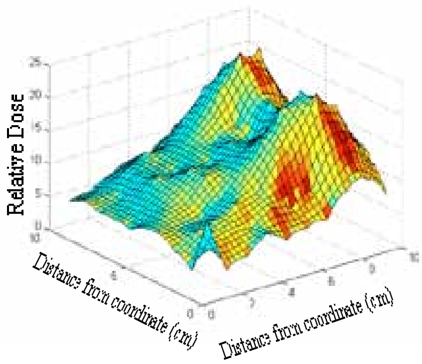

Fig. 4. Radiation field energy distribution of model 3, 4 spot sources on the plane through the center and parallel to the faces of the homogeneous water cube.

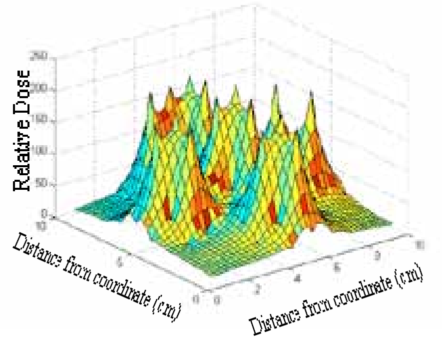

Fig. 5. Radiation field energy distribution of model 4, 5 spot sources aligned on a cross in the plane within the homogeneous water cube.

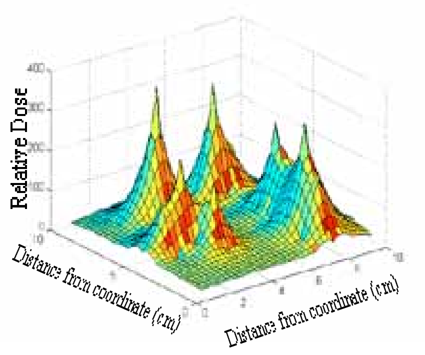

Fig. 6. Radiation field energy distribution of model 5, 5 spot sources aligned on a circle in the plane within the homogeneous water cube.

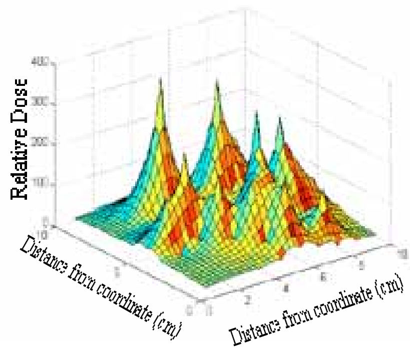

Figure 7 Radiation field energy distribution of model 6, 5 spot sources aligned on a circle in the plane within the inhomogeneous water cube.

Figures 6 and 7 give the results for a spot source array comprising 5 spot sources. Figure 6 shows that the absorption is stronger along the circle and the energy distribution is basically uniform in the homogeneous medium. Figure 7, however, shows that, in the inhomogeneous medium, the energy distribution of the radiation field is different because the aluminum medium, which has larger atomic number and density, absorbs more energy than the surrounding medium. There appears stronger absorption peaks in the aluminum medium and the energy absorption is much larger than the surrounding region. It follows that the energy distribution of the radiation field is dependent on the position and arrangement of the sources as well as the medium interacting with the sources.

4. Conclusions

Due to the complexity of human body geometry and constituent as well as the difficulty in analytical calculation of γ-ray radiation field for human body, which is a special medium, Monte Carlo simulation method was used to calculate the radiation field of ^{125}I spot source and spot source array. We obtained the three-dimensional distribution of the radiation field and investigated the influence of the medium homogeneity on the distribution of the radiation field. The simulation results show that the energy distribution varies with the arrangement of the spot sources and the radiation field distribution of the same spot source array also changes when the sources interact with different media. Medium with larger atomic number and density has stronger γ-ray absorption ability. These results provide important references for clinical medicine. One needs to consider not only the shape of the target region (tumor) but also the influence of the tissue density around the sources when designing treatment plan and choosing radiation sources properly so as to optimize healing effects [14, 15].

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of the simulation software for photons in medium

LIU Yi et al / Procedia Engineering 00 (2011) 000–000

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